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The Development of a Methodology for Quantifying Fatigue Crack Growth in Residual Stress Fields for Application to Rotorcraft Design and Maintenance

ABSTRACT: Progress is being made in currently ongoing research in the development and validation of methodologies for quantifying fatigue crack growth (FCG) in the residual stress fields. Shot peening and other types of surface treatments that are commonly applied to rotorcraft fuselage and drive train components induce these stress fields. This paper describes two independent research thrusts supporting this objective: the refinement of the threshold and near-threshold FCG databases for rotorcraft structural materials and quantifying the growth of small surface cracks that encounter compressive residual stress fields induced by shot peening. The Federal Aviation Administration (FAA) William J. Hughes Technical Center is supporting this research effort.

KEYWORDS: Rotorcraft, Damage Tolerance, Fatigue Crack Growth, Shot Peening, Residual Stress.

Introduction

The damage tolerance approach [1] is now well-established as the principal methodology for precluding fatigue failures in many types of weight-critical engineering structures, including transport aircraft. However, because of the high number of principal structural elements that exist, and the extremely high cyclic load frequencies that occur in rotorcraft [2], rotorcraft damage tolerance (RCDT) applications are considerably more challenging, and significantly less well-developed, than in transport aircraft. To support FAA rulemaking, the FAA Rotorcraft Structural Integrity and Safety Project, which is one of the research efforts under the FAA Aging Aircraft Program, has developed a comprehensive research and development program in which all phases of RCDT are being advanced.

Of specific interest here is the research that is being conducted to characterize fatigue crack growth for rotorcraft fuselage and drive train components. This work involves two main thrusts. First, because of the very small initial cracks that must be considered, there is a need to refine the threshold and near-threshold fatigue crack growth (FCG) databases for rotorcraft structural materials to account for the high cyclic loading frequency. Second, due to the extensive use of shot peening used in rotorcraft to retard and repress FCG, there is also a need to quantify the growth of small surface cracks as they encounter the compressive residual stress fields introduced by shot peening.

FAA research is currently attacking these two aspects of FCG independently with two different groups of researchers. The threshold and near-threshold database development and analysis work is being conducted for the FAA in collaboration with

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Mississippi State University (MSU), NASA Langley Research Center (LaRC), and NASA Johnson Space Center (JSC). Residual stress effects on FCG are being addressed by coordinated projects at the University of California, Irvine (UCI) and Wichita State University (WSU). This paper will describe the current progress by the research teams in each of these two areas.

Background

Rotorcraft represents a vital component of the international aerospace industry. In 2001, the 25 major helicopter manufacturers worldwide produced 846 new helicopters, 83% of which were for military applications with a total value of \$6.7 billion [3]. In the U.S. there are nine helicopter manufacturers that produce 26 helicopter models, ten of which are for military applications. While the total sales of U.S. manufacturers are predominately from military aircraft, there is still considerable activity in the commercial sector for which FAA regulation is needed to ensure flight safety. Rotorcraft structural components experience high-frequency cyclic loads in practically every flight regime [4]. While the effects of high-frequency cyclic stresses have always been a primary consideration in the regulatory process, modern rotorcraft usage has become much more diverse and, in some cases, significantly more severe. The FAA's responsibilities for increasing aviation safety in the rotorcraft structural integrity area are generally met by actions that are aimed at (1) reducing the number of fatalities caused by fatigue and fatigue-related failures in rotorcraft structure and (2) increasing the rate of detection of anomalies that cause the failure of the rotorcraft structure.

Currently, 14 CFR 29.571, Fatigue Evaluation, requires transport category rotorcraft structures to have the capability to continue functioning without catastrophic failure (fatigue tolerant) after being exposed to the repeated fatigue loads expected during the operational life of the rotorcraft. The fatigue tolerance evaluation is also mandated to include a determination of the probable locations and modes of damage caused by fatigue, considering environmental effects, intrinsic and discrete flaws, and accidental damage. Currently, fatigue tolerance requirements are satisfied by safe-life, flaw-tolerant safe-life (enhanced safe-life), fail-safe (residual strength after flaw growth) evaluation, or by a combination thereof. However, in 1999, the Technical Oversight Group for Aging Aircraft (TOGAA), a panel of independent experts, completed an in-depth review of the current fatigue and damage tolerance approaches. TOGAA strongly recommended to the FAA that a fracture mechanics-based damage tolerance approach, in addition to safe-life, should be used for determining inspection requirements, evaluating crack sensitivity, and evaluating designs and repair methods. As a result of this recommendation, the FAA developed a variety of research projects addressing damage tolerance requirements.

Determination of Threshold FCG Behavior

Laboratory techniques for developing fatigue crack growth data for metallic materials, and for characterizing them with fracture mechanics-based relationships, has been well-established for many years; e.g., with ASTM E 647 [5]. These have generally included determinations of the threshold by means of load-shedding measurements. Probably because FCG behavior in the threshold region has not often been crucial to determining lifetimes, while the inaccuracies inherent in the load shedding approach have

been widely recognized, they have not been a major concern. However, for rotorcraft drive train components where loads are accumulated so rapidly that miniscule cracks must be considered and where shot peening and other surface treatments are widely used to retard the growth of such cracks, FCG behavior in the threshold regime is of paramount importance. More accurately determining this behavior is a central focus of the FAA research.

The central issue is illustrated schematically in Fig. 3. Tensile residual stresses are incurred in the load-shedding procedure and produce remote closure that in turn gives rise to values of $(\Delta K)_{th}$, the threshold ΔK , that can be significantly unconservative. An alternative to load shedding is an approach called compression precracking (CPC). However, this technique is also accompanied by extraneous residual stresses, albeit compressive ones. As indicated in Fig. 3, the CPC approach tends to give $(\Delta K)_{th}$ values that are overly conservative.

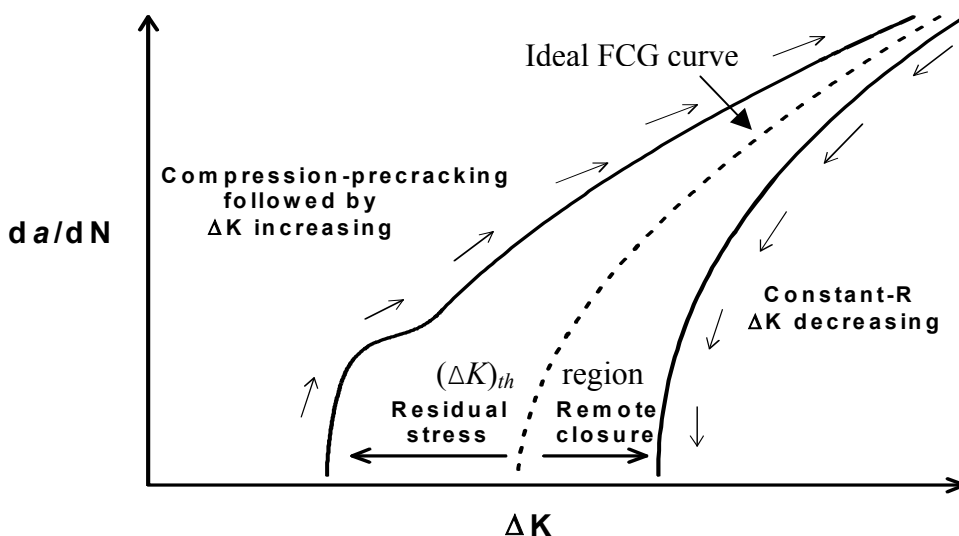


Fig. 3 – Schematic Representation of Load-Shedding and Compression Precracking Procedures for Determining Fatigue Crack Thresholds

The FAA is conducting research to identify alternatives and/or refine the conventional procedure for determining $(\Delta K)_{th}$ values and nearby da/dN versus ΔK behavior for the principal rotorcraft materials. This effort has two main objectives: (1) to identify the most appropriate manner for determining threshold FCG data and (2) by using this approach, develop a comprehensive database for rotorcraft materials. Specifically, combined experimental and finite element analysis work is being done at NASA LaRC that is centered on perfecting the CPC and the load-shedding methodologies. Researchers at MSU are seeking a basic understanding of the effects of FCG initiation procedures with the FASTRAN computer code [6], which is uniquely capable of accurately depicting closure from plasticity effects. NASA JSC is looking into the promising alternative of initiating cracks from very fine tipped (e.g., 0.001 inch) electron discharge-machined notches that have the potential of minimizing, if not eliminating, the residual stresses that result from preinitiation loading.

Crack closure can occur from several different physical effects. The most common manner is contact – either at the crack tip or along the faces of the crack remote from its tip – from residual plastic deformation arising from previous load cycles. This is the phenomenon that is incorporated into the FASTRAN code, and it is also implicit in most computational mechanics simulations of crack growth under cyclic loading. However, closure can also occur from surface roughness that arises from past deviations in the crack path, and from corrosion or other types of environmental effects. These effects are not readily handled by current analysis methods or by three-dimensional effects. Fig. 4 shows data [7] developed by NASA LaRC for aluminum alloy 2025 for which the behavior in the near-threshold region – possibly exacerbated by some or all of the above complexities – is currently difficult to analyze as evidenced by the fanning of data at the threshold region.

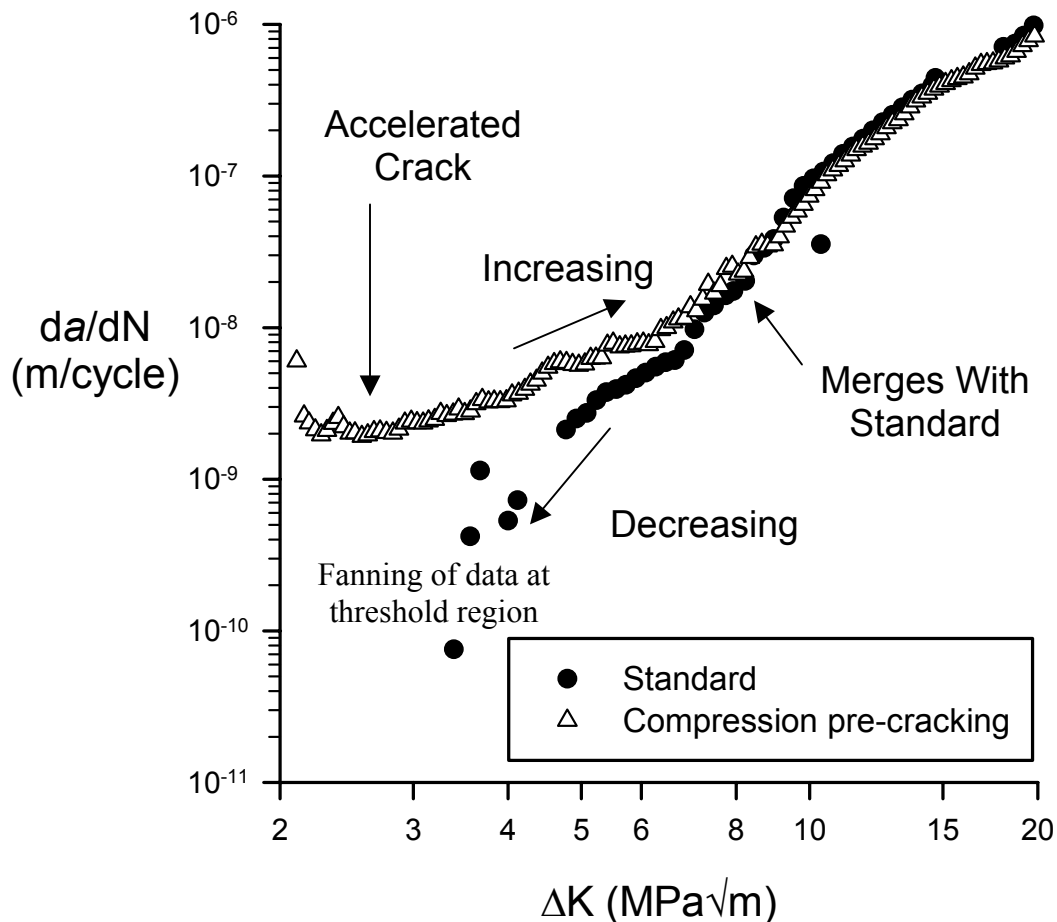


Fig. 4 – NASA LaRC Fatigue Crack Growth Data on Al 2025 for $R = 0.1$ at Room Temperature and Laboratory Air

Fatigue Crack Growth in Residual Stress Fields Due to Shot Peening

In this area, researchers at UCI are developing a first principles analysis model of the shot-peening process that is capable of determining the residual stress states that are induced by shot peening, and the attendant deformation states. Because the intent is to use these results as input to an elastic-plastic fracture mechanics analysis, the complete stress-strain information is essential.

Shot peening is a cold-working process primarily used to extend the fatigue life of metallic structural components by multiple repeated impacts of a structural component by small, hard spheres. As a result of the impacts, the surface of the component undergoes local plastic deformation, which forms a compressive residual stress field in the near-surface layer of the structural component. This near-surface layer compressive residual stress field is highly effective in precluding small surface cracks from initiating and propagating from the surface of a structural component, thus extending the fatigue life. This complex process has been modeled by UCI by, in effect, smearing the impacting spheres into a flat plate such that the impact is both uniform and simultaneous. The additional simplification to quasi-static conditions allows the elastic-plastic deformation process to be modeled precisely, with the stresses due to the permanent plastic deformation state to be determined accurately. A comparison between the predictions of the UCI analysis and experimental data [8] on a steel component is shown in Fig. 5.

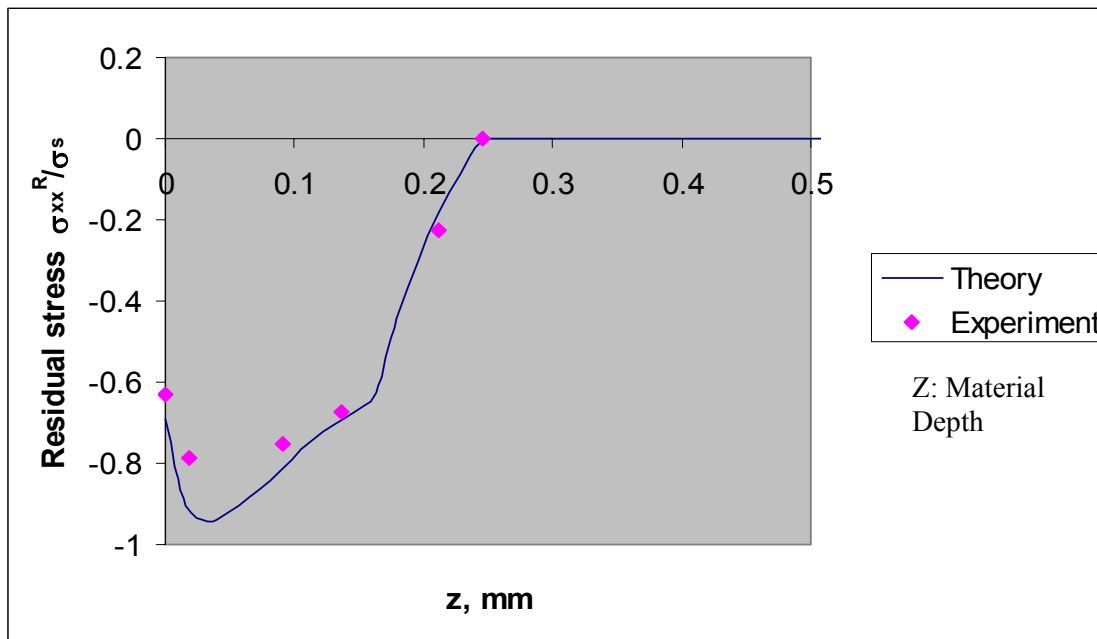


Fig. 5 – Comparison of Residual Stresses Predicted by the UCI Shot-Peening Analysis Model and Experimental Data for a Steel Component

The UCI analysis needs complete stress-strain curves together with other mechanical property information as input to the shot-peening model, and, later, to the elastic-plastic fracture mechanics analysis. Researchers at WSU are developing the data.

In addition, to have a critical assessment of the UCI analytical predictions, WSU is conducting tests on shot-peened materials with small cracks (e.g., 0.001-inch depth) in the shot-peened surfaces. WSU is also testing a plate with shot-peened surfaces and an edge crack. This configuration is shown in Fig. 6.

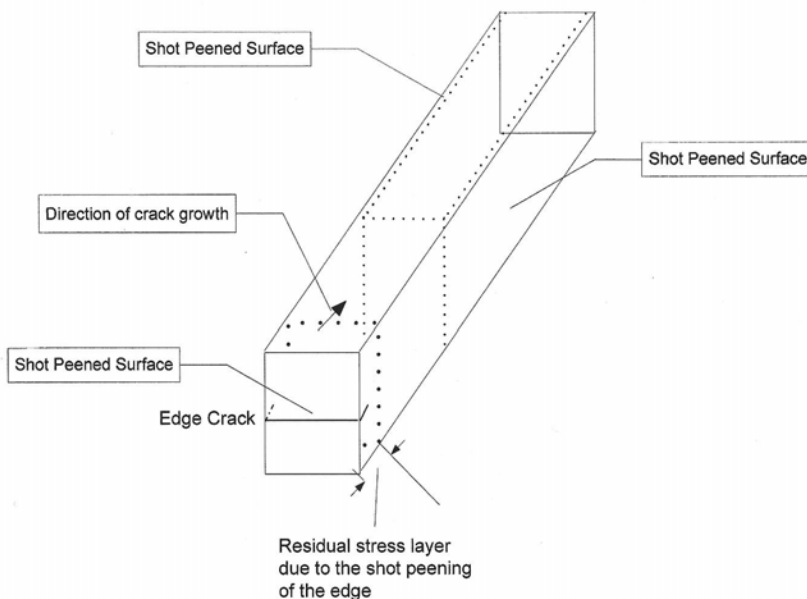


Fig. 6 – WSU Test Specimen for Measuring Rates of Fatigue Crack Growth in Residual Stress Fields Induced by Shot Peening

Summary

The FAA is conducting research on a broad range of challenges that must be overcome in establishing the damage tolerance approach for rotorcraft drive train and fuselage components. One aspect is the development and validation of analysis methodologies for quantifying fatigue crack growth in the presence of the residual stresses that are induced by shot peening and other types of surface treatments used by the industry. This work involves two main areas: (1) enhancing and refining current experimental techniques to obtain more reliable threshold and near-threshold fatigue crack behavior for rotorcraft materials and (2) extending current fracture mechanics analysis techniques to cope with pre-existing plastic deformation conditions. The progress that has been made in each of these areas has been outlined in this paper.

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